The Who, What, Where and When of Radar Targeting.

Key Note speech/presentation,
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Outline of presentation.

1. A brief look at some systems for which ATR is of importance.
2. An attempt to justify why ATR is important and therefore what drives the requirement for ATR from the users point of view.
3. A literature review including:
    - The problems of ATR using mmW radar and some of the techniques traditionally applied. This establishes the state-of-the-art. This section is the most significant element of the presentation.
    - Some further ideas which would appear to have potential and yet are little exploited/developed.
    - A comparison with the methods forming the state-of-the-art for electro-optic imagers.
4. Conclusions

Existing Systems

Existing examples of mmW radars employing ATR fall into three categories.

- Airborne Fire Control Radar
- Air launched anti-armour missile seekers
- Terminally guided sub-munitions

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Airborne FCR

AN/APG-78 "Longbow" is used on (W)AH-64D. The Longbow System is an integration of an all weather mmWave Fire Control radar with a Fire and forget missile in a lethal AntiArmour System. Longbow detects, locates and prioritises enemy tanks, air defence units, trucks and aerial targets.

Longbow FCR

- 35 GHz multi-mode FCR
- Classification of 256 targets
    - Doppler signature analysis
    - Range profiling, polarimetric

- Classification categories:
    - tracked vehicles
    - wheeled vehicles
    - helicopters
    - fixed wing aircraft
    - ADU (with RFI data)

- Prioritises targets
  - 16 highest priority displayed

The Apache flight crew work load is intense therefore a high degree of automation is required. Part of this is the prioritisation of targets which is only possible if they can be classified. Classification of ADU based on data merged from the RFI, a passive receiver used for emitter location.

Details of Longbow modes.

- Ground and Air targeting and terrain profiling modes
- Pulsed Doppler, Frequency agile
- Pulsed STI mode, Frequency agile, polarisation diverse
- Monopulse angular discrimination (elevation)
- Low Probability of Intercept
- Range vs. tank ~ 8km (moving), 6km (stationary)

Air launched anti-armour missile seekers

AGM-114L RF Hellfire is an air launched anti-tank missile fitted to the “Longbow” Apache (W)AH-64D attack helicopter.
It has a 35GHz active radar seeker which may be used in either LOBL or LOAL modes. It is truly a fire-and-forget missile.

Very little data is openly available but some details are presented below.

- 35GHz active seeker
- Pulsed mode
- Range profiling
- Length 69” (175cm)
- wt = 108lbs (49kg)
- Range = 8km
- Range vs. MBT ~ 3km (estimated)

Some interesting features emerge from observation of videos:

1. Dive angle in terminal phase about 20 degrees.
2. Clutter backscatter is fairly low below 20 degrees.
3. Strike point is where turret meets hull (possible aim point) i.e. very strong source of reflection and a weak point where armour would more easily be defeated.

Air launched anti-armour missile seekers

Brimstone is another air-launched anti-tank missile. It uses the same missile airframe as RF Hellfire and is perceived as an upgrade to Hellfire.
Brimstone will be used from a variety of strike aircraft.
Brimstone has a highly sophisticated 94GHz active radar seeker which affords a fire-and-forget capability.

- Air-launched anti-armour missile
- 94GHz imaging radar seeker
- Aim point selection
- Pulsed Doppler, polarisation diverse, pulse compression
- Monopulse angular discrimination
- LPI
- Range vs. tank ~ 2 km
  (estimated)

Typically, 3 Brimstone missiles are fired. The missile dives down to fly out at an altitude of ~300m. The seeker goes active immediately and is used to detect the ground for the fly-out phase. Seeker detects changes in ground contours to adjust flight of missile and scans for targets. The seeker includes many ATR features. LOAL for terminal phase guidance used.

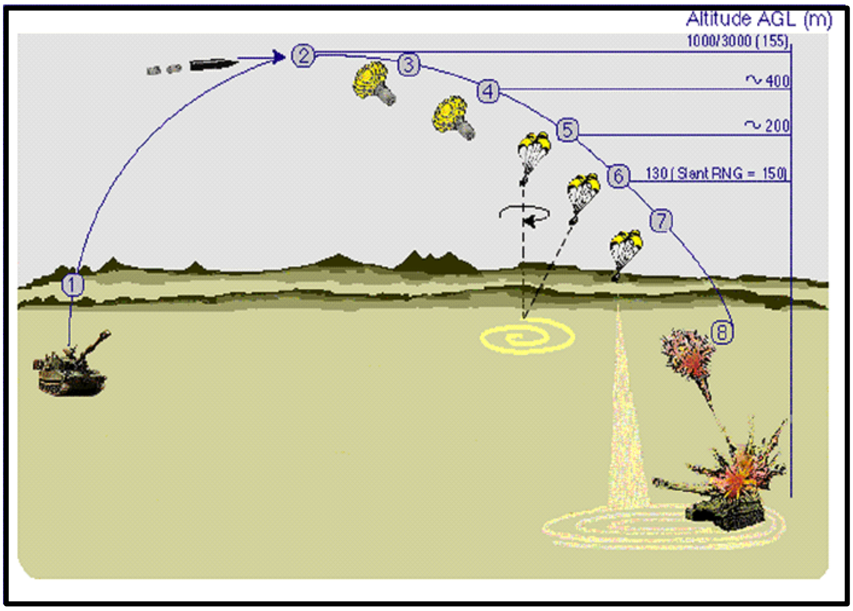
Terminally guided sub-munitions

Search And Destroy ARMour (SADARM) is a gun launched anti-tank TGSM. Other examples of similar weapons from other countries are available.

SADARM includes a tri-mode seeker of:

- Passive IR array
- Passive mmW sensor
- 94 GHz active radar – low power, short range, fairly basic system
- Terminally guided sub-munition
- 94GHz active seeker
- FMCW
- Range vs. tank ~ 100s metres (estimated)
- No ATR facility

Seeker sensors designed to detect armoured vehicles and between them have some sort of ATR capability, although little ATR capability resides within the radar. Seekers identify tank targets not already killed.



SADARM makes an overhead top attack (OTA) using an explosively formed projectile (EFP) warhead. This is illustrated above.

Joint Common Missile (JCM)

Air to surface missile designed to attack moving and stationary high value land and naval targets. Likely to replace Hellfire in long term.

Tri-mode seeker:

- semi-active laser,
- millimeter wave radar
- focal plane array radar.

JCM's physical configuration [1] is expected to be

- diameter 6 inches (15.25cm)
- length 50 inches (127cm)
- weight $\leq$ 70 pounds (31.8kg).

Existing Systems – Summary

Some trends emerge from the examples considered in previous paragraphs:

1 mmW radar with ATM is used for target acquisition. Here it is important to target only legitimate military targets. Examples currently include the Longbow system but in future can also be expected to cover airborne multi-mode radar for ground targeting and air-air modes, ground based air defence systems, wide area and spotlight SAR systems, although these latter systems may not all be mmW.

2 Another recurrent theme is the use of mmW seekers incorporating ATM for air (or gun) launched anti-armour guided weapons.

3 In many of the systems considered, a mmW radar is but one of a suite of sensors operating in different bands of the EM spectrum. Here we have the first suggestion that targeting decisions are more reliable if based on the fusion of data from the various sensors. Successful mmW radar ATR could lead to simpler seekers OR we acknowledge that mmW radar cannot solve the ATR problem on its own but plays its part in doing so.

4 In such systems (2, above) we see that the targets of interest are armoured vehicles, primarily the MBT. The current drive has therefore concentrated on the detection of such vehicles with the emphasis on the positive identification of MBTs.

Requirement
Some questions.

What drives the requirement for ATR?

- location and identification of targets of interest in wide area imagery to ease the burden on image analysists
- precision attack against legitimate targets
- reduction of fratricide
- assistance to targeting decisions

Where is ATR required?

- deep target attack ISTAR
- short range weapons aiming and guidance
- land, air, sea, particularly *ground based* & *littoral waters*

Should we trust a life/death decision to a machine?

Most of the points above are self-explanatory. [2]

Nothing above requires (mmW) radar to be capable of ATR. The military user does not care which sensor(s) perform the ATR job, as long as it gets done. Nevertheless, it is incumbent on a mmW radar, perhaps due to their prevalence as the primary sensor in a guided weapon seeker, especially in the air-launched anti-armour role.

Perhaps the only legitimate answer to the last question is to say “only if we can be confident that the machine is more reliable than a human operator”. This gives some indication of the level of performance required before ATR systems with this degree of responsibility will become acceptable. ATR is sometimes perceived as a means of adhering to RoE which require a positive target id; is a machine based id adequate? Who is responsible for errors; the military operator or the designer of the ATR algorithm? This is a highly political area.

Some quotations regarding ATR.

- INTENT
  "The military are not merely interested in recognition and identification but need to know a target's *INTENT*."
  - Now the sensor suite must be capable of mind-reading.

- HOLY GRAIL
  "Automatic target identification is the Holy Grail."
  - This is the most demanding point on the wish-list.

- RADAR ATR
  "The burden of ATR does not necessarily rest solely on radar."
  - Other sensors are likely to be required.

- MULTI-APPROACH
  "Automatic target identification can only be met by the data fusion of a multi-sensor, multi-band approach."

  Different target data will be required from a suite of sensors. It's no good if they all give the same data, so they must operate in different bands to yield differing data. Localised ATR processing of individual sensor is giving way to data fusion. Current trend is towards probabilistic approaches such Bayesian methods.

- A & I-
  "Does the "A" in ATR stand for ***Automatic*** or ***Assisted***?
  Does the "I" in ATI stand for ***Identification*** or ***Indication***?"

  The degree of difficulty increases as we go from assisted to automatic and also in going indication to identification. Assisted is consistent with requirement for assisted target decision making whereas automatic suggest the machine makes an autonomous decision. Indication means detection whereas identification requires intra-class separability.

  Automatic Target Identification may be seen as the Holy Grail but ***Assisted Target Recognition*** is perhaps a more realistic expectation over the next few years.

- TARGETS
  "What are the targets? This is something we have difficulty in defining."
  - We cannot define what a legitimate target is (does the car contain innocent civilians or does it contain a car bomb?). So how should we program the ATR algorithm?

Review
The literature review covers the areas listed below and forms the bulk of these notes.

- The special nature of (mmW) radar
- Criteria for detection/recognition/identification
- SAR/ISAR imaging
- Resolution capability
- Image recognition
- Range profiling
- Novel & emerging ideas
- Comparison with EO imagers

Special Nature of (mmW) Radar
Radar is traditionally seen as a sensor which lacks the resolution necessary for target recognition. EO imagers, conversely, have a fine resolution and permit recognition. Radar is therefore not a natural choice of sensor for ATR purposes, however, it does have several key advantages with respect to EO imagers which are summarised below.

- Radar is *active* and *coherent*.
  - Leads to direct measurement of *range* and *Doppler*.
- Radar uses a long wavelength.
  - Leads to *all weather* capability
  - Can penetrate dielectrics (foliage, camouflage etc.)
  - Low resolution (traditionally)

In comparing mmW radar to traditional cmW radar we expect there to exist the differences summarised below.

- Use of millimetric wave radar.
  - Finer resolution and smaller radars feasible
  - Short range
  - Radar signature dependent on finer level of detail e.g. surface roughness
  - Clutter differs

- Greater sensitivity to wavelength dependent effects.
  - Angular variation

In truth, fine resolution can, in theory, be achieved at any frequency given sufficient aperture, bandwidth and processing time, however, it is more practical to implement at mmW frequencies.

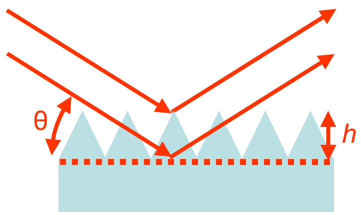
mmW radar does not differ in any significant way to cmW radar but the use of such high frequencies enhance certain effects and so bring about the possibility of ATR. Almost any aspect of radar performance is related to its frequency.

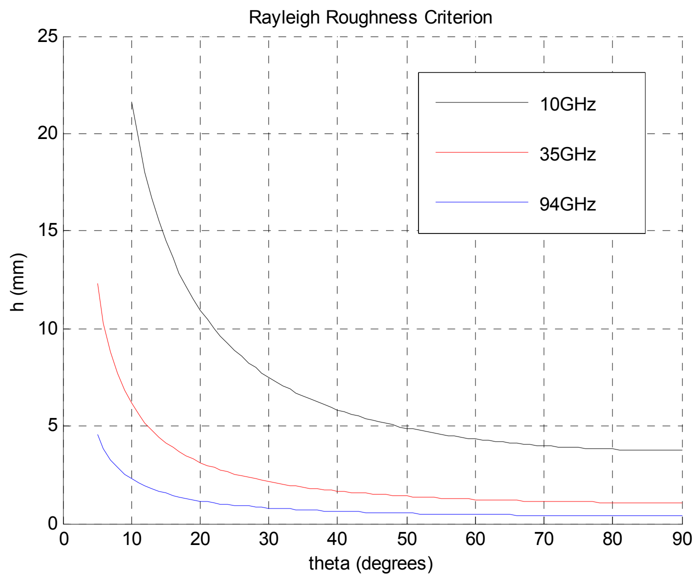
Of particular interest is the variation of target signatures with frequency. In general, we expect to see that the radar signature of a target (or clutter) become more sensitive to a finer level of detail e.g. surface roughness.

Targets are likely to be detected in amongst clutter so the frequency dependence of both target and clutter signatures are relevant, e.g. detecting vehicle targets in a SAR image.

Scenes and signatures will be more sensitive to wavelength dependent characteristics in the mmW band, e.g. target signatures are likely to be more sensitive to the monostatic viewing angle which has profound implications for ATR.

Physics of EM Interaction with Target
Surface Roughness -- Rayleigh Criterion





The above diagrams illustrate the Rayleigh roughness criterion.

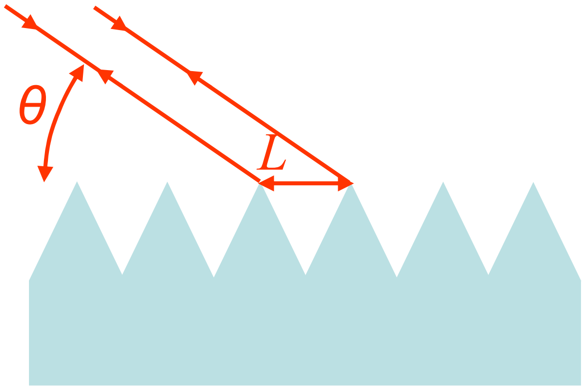
The regions BELOW the curves in the graph are considered SMOOTH and result in specular reflection.

The regions ABOVE the curves are considered ROUGH and result in diffuse reflection.

Thus h = 5mm is smooth at 10GHz below 49 degrees but rough above 49 degrees or at 35GHz above 12 degrees or at 94GHz above 4 degrees.

Surfaces tend to appear much smoother at low angles and at low frequencies.

Surface roughness – Bragg Scattering



There is a strong back reflection when $L = \dfrac{n\lambda}{2\cos\theta}$ $(n = 1, 2, 3\ldots)$

There are many combinations of angle, wavelength and surface texture geometry which can result in strong scattering (assuming a regular textured pattern). For example when the illumination is perpendicular to the facets and when the angle at the bottom of the groove = 90° (for $\theta \geq 45°$). They will also often exhibit strong polarisation characteristics. A particularly interesting target would be a golf ball.

Random rough surfaces have been modelled with a random phase component [3] (actually, not completely random).

Roughness

Dielectrics in the mmW band:

- tend to have greater loss tangents
  e.g. water $\tan\delta \sim 0.15$ @ 3GHz, 1.2 @ 35GHz, 2 @94GHz (Alabaster [4])
- interference effects from thin layers
  e.g. glass windscreens
- wavelength on same scale as long chain polymer molecules
  e.g. composites
- roughness appears not to be such a dominant factor as one might think
- (diffuse) scattering is highly angular dependent
- roughness may be modelled by inclusion of random phase shifts and/or empirically determined parameters
- roughness better modelled using “exact solver” codes
- target “speckle” is wavelength dependent.

The last 4 points above come largely from [3].

Several sources seem to suggest that roughness is not as significant as may previously have been thought:

- Firstly, my own work with dielectrics supports this.
- Secondly, modelled data based on targets constructed from many, smooth facets is in close agreement with measured data (e.g. [5]). Discrepancies are seen for cross-polar RCS at certain angles, which is consistent with expectations of scattering from rough surfaces as predicted by Bragg and Rayleigh formulae.
- Thirdly, in [3], Le, Coburn and Nguyan remark that the roughness parameters *range* are typically smaller than expected. The authors conclude that for Xpatch modelling 3 rays per wavelength is a good compromise to faithfully represent the RCS yet not incur too long a computation time. They found that RCS could be modelled using a roughness parameter which varied with the cosine of the depression angle of view.

Perhaps the threshold on the level of detail which is necessary to faithfully model the RCS of a target is somewhat greater than the Rayleigh roughness criterion.

Speckle is the variation in RCS of scatterers within a SAR image. It arises due to movements on the scale of the wavelength [6]. Therefore, the mmW band will be more sensitive to speckle than cmW band.

Target returns are likely to decorrelate more quickly when viewed at higher frequencies.

Detection/Recognition/Identification Criteria

Imagery interpretation:

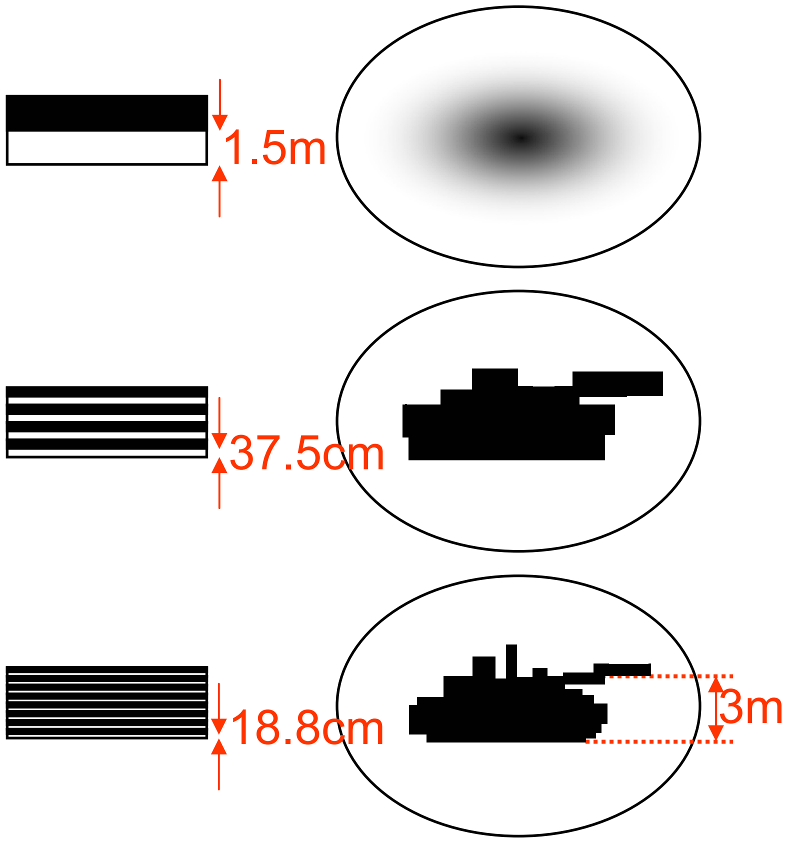
Detection: *the discovery of the existence of an object without its recognition*

Recognition: *The ability to fix the identity of a feature or object within a group type i.e. inter-class discrimination*

Identification: *The ability to place the identity of a feature as a precise type i.e. intra-class discrimination*

These definitions come from ATP 47(A) and are reproduced in [7].

The Johnson Criteria



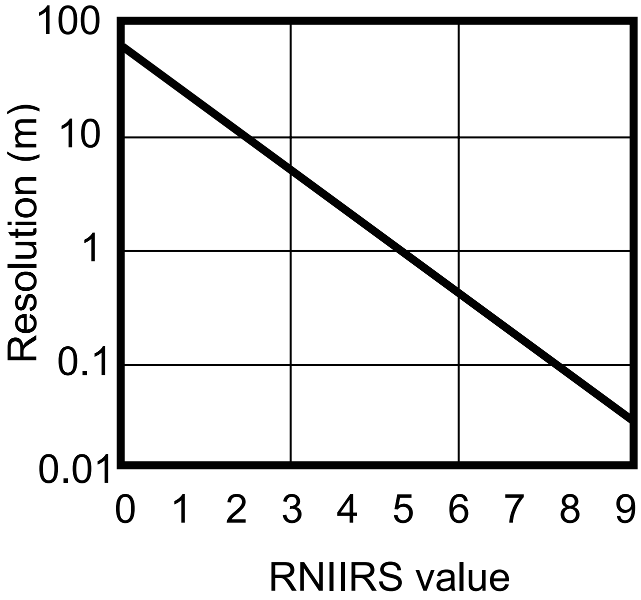
The Johnson criteria [8] were derived from extensive trials using trained observers with a variety of test objects and a variety of (EO) imagers and under a variety of test conditions. All criteria are based on a 50% level from the observers.

The target range was reduced until the target was detected/recognised/identified by 50% of the observers. At the d/r/i ranges the targets were replaced by a two tone bar pattern of similar contrast to that between target and background. Various spatial frequencies were trialled to find the resolvable limit. The resolvable cycles per minimum target dimension for d/r/i were found to be:

- Detection: approx. 1 cycle per minimum target dimension
- Recognition: approx. 3 to 5 cycles per minimum target dimension
- Identification: approx. 6 to 7 cycles per minimum target dimension

For specification purposes d/r/i = 1/4/8 cycles per min target dimension (as on slide) Whilst this is interesting to note it does not imply anything about the resolution required for imaging radar ATR.

The Radar NATO Image Interpretability Rating (RNIIRS)



Capability	RNIIRS
Recognise large static targets	1-2
Detect mobile targets	3-4
Recognise mobile targets	5-6
Identify mobile targets	6-7
Battle damage assessment	7-8

The RNIIRS values are described in [9]. RNIIRS scale of 0 to 9 define radar resolution for specific capabilities.
The RNIIRS and Johnson criteria are approximately equivalent, e.g. recognition of mobile target (minimum dimension = 3m)

- Johnson criterion requires resolution of 37.5 cm – previous diagram
- RNIIRS value required is 5-6, therefore resolution of 1.0 to 0.5m

As an example[10]:

Watchkeeper URD 4002 Annex E
Resolution requirements: d/r/i = 1.0 to 1.5/0.5/0.15 m

Radar ATR

Can radar provide automatic target recognition?

The $64k question. To which the answer is a highly qualified "yes".

Pcc of 80-95% regularly achieved in "special operating conditions" BUT *Pcc* not much better than random chance in realistic battlefield "extended operating conditions (EOCs)"

The difficulty is in maintaining performance in the following EOCs:

- **Obscuration** e.g. smoke, haze, fog, rain
- **Environment**, i.e. clutter which adds extra data to the target image.
- **Occlusion**, hidden parts of targets e.g. tank dug-in, revetments, which denies target data from the image.
- **Overlapping nearby targets** in which the signatures from more than one target overlaps
- **Configurational changes** articulation of turret/gun, hatches open/closed, tools and equipment on outside, angle of view, target orientation and scale (imaging). Small structural changes in the target have significant effects on its radar signature. This becomes increasingly more so as frequency increases into the mmW band. Thus model data and training data must be made on the basis of fine structural detail.
- **Serial number** the consistency of (supposedly) identical targets.

However, some headway into the problems has recently been achieved e.g. [11].

The brute force approach is to have training data corresponding to every eventuality but this requires an enormous computational effort (especially for near real time operation).

A better but less reliable approach would be to use algorithms/data which can generalise, particularly for inter-class separability e.g. [12] (Maskall, Webb). This had partial success only and just proves the requirement for faithful training data.

Recent work to consider robust ATR in EOCs – see [13] (Hummel), [16] [17]. Targets identified with near certainty using 30cm resolution SAR image, even for 30 target types in mission set. *Pcc*: 80-90% for EOCs explicitly considered (configurational changes, articulation of M109 turret/gun). Obscuration by walls (revetments) and targets in close proximity are still challenging. Problems arise where system attempts to achieve robustness by ignoring variability. This supports the notion that model based technology holds the key to the transition of useful ATR into operational use.

SAR/ISAR Imaging

State-of-the-art SAR/ISAR can obtain range and cross range resolution down to 10cm., see Van den Broek [14] 35GHz ISAR images of 10cm/30cm resolution.

Target recognition is a matter of data dimensional reduction e.g. spot-light SAR image of 1km x 1km at 30cm resolution has 107 pixels. This must be reduced to the identification of *x* targets and the recognition of *y* target classes giving a dimension of *xy*. Data dimensionality reduction from 107 pixels to *x* chip sets of 2500 pixels corresponding to *x* targets of *y* classes (dimension xy) e.g. 20 x 20 = 400.

Multiple stages of processing include:

- extraction of "focus of attention" or ROIs e.g. chip sets of 50 x 50 pixels
- image recognition/identification.

This is a huge area of research with masses of publications. The US MSTAR (Moving and Stationary Target Acquisition and Recognition) program gave a considerable impetus to research in this field.

There are excellent reviews of SAR [15]-[18] Novak et al. The following can only scratch the surface of the proverbial iceberg.

30cm resolution corresponds to RNIIRS value of 6 (recognise mobile targets) or recognition of <3m target by the Johnson criteria.

10cm resolution corresponds to RNIIRS value of 7.5 (identification and BDA) or identification of >3m target by the Johnson criteria.

This illustrates that radar does possess the resolution for recognition/identification using EO/optical standards. In spite of this higher resolution SAR data for robust id in EOCs is sought.

There are inevitably further stages to the processing e.g. determining target orientation, but these two always exist and are reviewed in the next few sections.

Extracting the Regions of Interest

This sub-section is largely based on [19] Kaplan, except where stated.

FOA extraction should be quick and easy (since the more computationally demanding ATR algorithms are to follow). However, it is worth investing some effort to get it right as it is instrumental in setting the *Pd* and *FAR*.
Traditional approaches are based on some sort of CFAR processing.

Traditional 2 parameter CFAR extracts ROIs based on their brightness and contrast since regions containing targets are likely to have stronger scatterers than surrounding clutter. Most methods assume Gaussian clutter, which is not always realistic. This is the traditional baseline standard.

Problems occur due to misinterpreting regions of bright clutter (e.g. from trees, buildings) as possible FOAs and in contending with realistic clutter distributions.

Recently, some non-Gaussian clutter CFAR techniques have been used (Weibull and K-) but these are computationally more demanding.

Research effort has gone into methods exploiting the spatial properties of targets. Some methods design linear features to optimise the difference between, say targets/clutter, similar to matched filtering. This is computationally demanding so unsuitable for FOA. However, these methods have been used for the target recognition e.g. the order statistics filter (OSF) detector – good at picking out target sized features but prone to false alarms.

Texture based features also a subject of recent research. These exploit differences in the spatial distribution of reflected energy from targets/clutter over localised regions. Texture segmentation can identify varying terrain types which can provide valuable contextual information [20] Britton, Evans.

An extended fractal/2 parameter CFAR approach has been shown to be a good compromise between performance and speed. The EF element introduces a size sensitivity (can be tuned to give peak output for some specific target size) and can adapt to the clutter level. It is fused with 2-parameter CFAR for brightness/contrast sensitivity too and gives lowest FAR. (The EF also gives peak output for appropriate size of darkness. Possible ambiguity reduced using 2 parameter CFAR.)

Additional Processing Stages

Further intermediary stages of processing may be introduced to help reject clutter, reduce FAR [17] and determine target orientation (which may be beneficial to the ATR stages) [14].

Indexer to label candidate targets. FOAs subjected to a screening process based on size, shape, fill ratio, pattern recognition etc. to reduce false alarms.

Orientation of targets may be determined by applying transforms to detect the edge of the major axis (Sobel operators, Hough transform, Radon Transform). Orientation to within ~ 10° can be achieved but may have 180° ambiguity.

Image may be normalised (normalised mean) i.e. a brightness normalisation.

Target Recognition Techniques

Template matching e.g. use of mean squared error (MSE) algorithm. Images compared with “training” data [16] **[17]**.

- ROIs declared as target type or dismissed as clutter.
- Problems with occluded targets and articulated targets.

There appears to be some contradiction here because Novak [16] claims that the MSE classifier has had some success for half and full revetment T72. However, this work also confirms that turret articulation degrades *Pcc* for rotations of 10° away from template data. They propose the requirement for templates for every 20°. [This is probably too few especially for the mmW band – see the discussion on the sensitivity to aspect of range profiling.

Several researchers [13] adopt the Predict, Extract, Match Search (PEMS) method of target recognition/identification to match measured target signatures to signatures held in a database.

Point of Note.
Sometimes, synthetic models are produced from simulations of the targets (perhaps because real measured data is not available for every frequency/angle/orientation etc). This is not so desirable because of model inaccuracies/mismatches and generally results in lower *Pcc*. XPatch is a well respected software tool to produce such models (in the form of SAR images). Research effort has been directed specifically at the efficacy of models such as Xpatch, Fermat, Rapport and Facets e.g. [3]-Xpatch.

Methods based on relative dimensions of scatterers. [11].

- Still requires training data.
- Optimal number of scatterers (30 – 50).
- *Pcc* remains high for 60% occlusion.

Best for targets with large relative distances between scatterers (rather than close clusters).

Statistics of radiometric, geometric and polarimetric features.
Van den Broek et al., [14].
No single feature is a robust discriminant. *Pcc* generally improves with

- resolution (10cm better than 30cm)
- number of features
- known target orientation

Neural Networks and evolutionary algorithms. [21][22][23]
Neural networks have long been applied in pattern recognition. They have an ability to generalise dependent on the neural structure. The neural structure may be optimised using an EA. [23] Harvey, has used an EA to evolve an artificial neural network to detect the perpendicularity in order to make edge detection for the detection of man made structures such as buildings.

Statistical methods to determine the class and orientation of the target in an image chip.
DeVore and O'Sullivan et al., [6] [24].

Pixel values in chip sets are matched to various PDF. Pixel values are transformed in an attempt to yield a Gaussian PDF. Transformation giving best Gaussian fit reveals original PDF of data. Data PDFs considered are:

- (Conditionally) Gaussian model.
  Complex pixel vectors Gaussian of zero mean, match to variance.
- Log magnitude model.
  Pixel magnitude squared is log normal, match to mean (dB)
- Quarter Power model.
  Square root of pixel magnitude is gamma PDF, match to mean.
  Requires windowing and interpolation to refine orientation estimation.

Performance of all these is a trade with complexity. Conditionally Gaussian is best (bold) both in terms of orientation estimation (accurate to around 5 -100) and *Pcc* is as high as 98.75%.

Additionally, there are many examples in the literature of applying a wavelet transformation to a 2D image as part of feature recognition techniques – not dealt with here. This is not an exhaustive review because of the considerable volume of the literature in the field.

Target Recognition

Considerations

Many model based algorithms for ATR are based on a system of *votes* of multiple hypotheses. Various statistical combinations threshold the votes to declare the target type. (Proportional representation *NOT* first past the post.)

Bayesian approach based on mixed models helps achieve generalisation/robustness and greater confidence (Maskall, Webb [12][26]).

There is an optimum to the model complexity (for fixed size target set), see O'Sullivan, DeVore et al [25][6]. Reducing data to retain those components which correlate well against model increases performance and reduces computation. Also supported by Maskall, Webb [12].

Some algorithms search for positive proof of target type [6]. This is acceptable for a limited target set.

Comparison of ATR performance is fraught with difficulty due to the uniqueness of the conditions.

Contextual information can help to resolve true targets of interest from other details [20][27]. It might go some way to shedding light on the *intent* of a target. Contextual information could include position of target with respect to other features (e.g. proximity of target to a road, runway) and track history.

Range Profiling

1-D Range profile is a 2D (I)SAR image projected onto the range coordinate, as such it is less computationally demanding. Images are processed using (weighted) FFT or High Definition Vector Imaging processing techniques (HDVI) techniques (SAR – from which range profiles may be derived) and template matching. HDVI is a super-resolution technique and improves *Pcc* on otherwise lower resolution images by a factor of 2 [28].

Many other processing techniques have been investigated such as wavelet transformation in order to de-noise synthetic model templates and reduce the profiles to their salient features [29].

There are difficulties in measuring range extent of targets due to self masking, especially at low grazing angles (depends on how range extent of target is defined) see Schimpf [30].

The range profile is very sensitive to target aspect, particularly at mmW [31]-[34]. Sensitivity to target aspect may be reduced by non-coherent averaging over a span of aspect angles.

Pcc improved using multiple looks at multiple aspects spaced at fraction of degree [32]. Long processing intervals reduce target speckle. *Pcc* sensitive to SCR. Range profiling best adopted for ***moving*** targets.

1-D cross range profiling has been attempted using ISAR techniques (but with little success) [35]. This uses FFT techniques. The Problems are non-uniform target rotation, particular severe for large targets (airliners), but can to some extent be accounted for. Scatterer migration through range cells (MTRC) blurs an ISAR image towards its periphery but blurs the whole of the cross range profile (since a cross-range profile is the projection of the 2D ISAR image onto the cross range axis).

Range profiling is best used for moving targets where it is awkward for SAR. Aspect sensitivity is of major concern and would tend to worsen at higher frequencies. Use of mmW band makes high resolution radar more practicable but otherwise is less desirable.

Sensitivity to aspect

Liao, Bao, Xing [31]. HRRP decomposes into scatterer auto term (SAT) plus scatterer cross term (SCT) angular sensitivites.

SAT is integration of scatters' energy within a range cell.

SAT depends on:

- Positions and strengths of scatterers – usually fairly consistent over 10°
- Scatterer shadowing – worse at low grazing angles
- Scatterer migration through range cells (MTRC)
    - Tolerance condition $\delta\varphi MTRC \leq c/2BLx$

      e.g. B = 500MHz ($\rightarrow$ Rres = 0.3m), Lx = 7m gives $\delta\varphi MTRC \leq 2.4°$

The MTRC tolerance condition leads to aspects of a few degrees. This matches the typical averaging used whereby range profiles every (approx) 4 degrees are used.

SCT is the tolerable variation of the range profile and is much more sensitive to aspect than SAT. SCT depends on correlation of range profiles at different aspects and is about an order of magnitude more aspect sensitive than SAT at cmW. e.g. correlation between 2 range profiles reduced to 0.75 over 0.3° (1GHz) to 0.1° (2GHz). SCT variation with aspect will be virtually intolerable in the mmW band.

Range profiles must be averaged over a span of aspect angles to reduce the aspect variation, but over what angle?

ISAR images have much reduced SCT because scatterers are resolved in the cross-range dimension. Since a range profile is the projection of an ISAR image onto the range axis we can base the required angular averaging on the aspect variation necessary to acquire a decent ISAR image. However, a well focussed ISAR image is achieved over an aspect variation of: $\Delta\varphi \geq \lambda/2.\Delta Rx$

- At 3.2cm wavelength (I-band) this requires an angle no less than 3° (similar to the MTRC condition).
- At 3.2mm wavelength (94GHz) this requires an angle no less than 0.3°.

Therefore, averaged profiles may be required at finer angular intervals in mmW band than at cmW band.

Range profiles must be aligned before averaging which introduces complexity. Bispectrum methods based on Fourier transforms into 2D frequency space ease the complexity and is invariant to misalignments. ATR can operate on the bispectrum but it is computationally expensive. Bispectrum slices (axial, radial, diagonal) reduce dimensionality. Circularly integrated bispectrum found to give best ATR performance.

The natural assumption is to presume ISAR data is superior for ATR purposes as it contains more data but averaged range profiling is less sensitive to aspect than the ISAR image and so is a better choice for ATR. (Processing complexity for image recognition has already been covered.) However, an ISAR image is more sensitive to aspect variation than range profile and so may be the better choice. Range profiling is used extensively for airborne targets.

Radar Vibrometry – *Micro-Doppler*

One of the most important challenges facing radar systems today is to derive information that can lead to reliable target classification. The vibration signature of targets will contain additional information for classification. Radar systems have traditionally used reflectivity to detect objects and determine their location and velocity. High resolution has been used as a method of providing a more detailed signature for target classification with limited success. Recently there have begun to emerge a class of sensors known as 'radar vibrometers' aimed at measuring the vibration signature of an object e.g.[36][37]. Vibration causes phase modulation and relatively simple concepts based on 'laser vibrometry' principles offer micron movement detection [38]. Since sensitivity improves with increasing frequency and thus very fine Doppler discrimination (as opposed to measurements of bulk velocity) is achieved. Vibration is also likely to modulate the polarisation of the target signature.

The technique has the potential to determine whether a vehicle engine is running which may give some indication of the intent of the target. In addition it may be able to detect structural resonances in the vehicle which may be characteristic of a particular type of target.

On the other hand radar vibrometry requires that radar very low phase noise transmitted signal and LO.

Combined with high resolution radar vibrometry will lead to more robust classification of objects through better and more complete use of radar data than is the case today.

Novel SAR Techniques

3-D ISAR imaging on manoeuvring target using 3 receivers in a plane orthogonal to the line of sight.

Wang, Xia and Chen [39].

- 3 offset imaging planes (data is phase shifted).
- yields known cross range (Doppler) scale even if target rotational movement is unknown.
- similar to Lippman photography

Non-linear SAR

The platform flies a curved path to decouple the Doppler history associated with target motion with that due to platform motion.

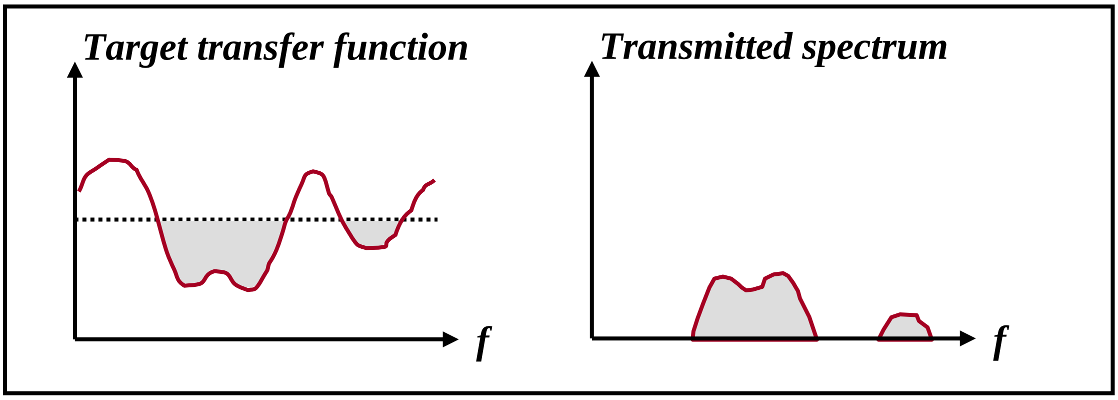
Stepped frequency SAR -- Matched Illumination

A radar system can be used to determine unknown characteristics of a target. In information theoretic terms it can be used to reduce the initial uncertainty concerning the target.

Given a target frequency response $H(\omega)$ and a received spectrum $V(\omega)$ then the radar measurement maps the information in $H(\omega)$ into $V(\omega)$.

The problem is to maximise the mutual information $I(H(\omega);V(\omega)|E(\omega))$, i.e., the amount of information that the (sampled) spectrum $V(\omega)$ provides about the target response $H(\omega)$.

In practice $E(\omega)$ is the transmitted spectrum thus $I(H(\omega);V(\omega)|E(\omega))$ represents the amount of information that $V(\omega)$ provides about the target response $H(\omega)$ when the transmission was $E(\omega)$.



For HRRR, maximum SNR is obtained for:

- matched receiver
- matched transmitted waveform
- measure of both.

However the effect of optimising the transmitted signal for information transfer is to 'fill in' the gaps in the targets frequency response as illustrated above [40].

Comparison with EO Imaging

EO imagers can achieve cm level resolution in real time. ATR based on image recognition algorithms however EO sensors do not enjoy such diverse techniques as radar [41].

Current image recognition methods for research include:

- Fourier descriptors,
- Moment invariants, [42] Luckraft, Jenkin, Richardson.
- Hyperspectral imaging,

Various others including synthetic aperture techniques used for astronomy and civilian applications.

ATR in special operating conditions is reliable, ATR in realistic battlefield situation is poor (scattering, attenuation through atmosphere is a major problem). Superior algorithms and computing power are required.

Whilst the technology differs Radar and EO sensors are in almost identical situations.

Conclusions

- Radar resolution matches the requirements for EO imagers for recognition/identification.
  Lack of resolution is not the issue.
- Reliable recognition is achievable in benign conditions; but not in a realistic battlefield situation.
- Future advances sought in computing capacity and/or processing algorithms possibly in those techniques which mimic the natural world e.g. neural networks and evolutionary algorithms.
- Better performance likely by fusion of several ATR techniques – see [44] French MILORD project
- Several potential methods are under-exploited.
- Even better performance likely by the fusion of multi-sensors in different bands. US Navy ARTIST is a development radar program to develop future radar techniques. Identification is not attributed to the radar, or any individual sensor, but to the fused data of all the sensors [7] [43].
- Assisted target recognition is the most realistic goal (for a single radar sensor).

Personal Reflections

1 A lot of research money and effort has been invested in this problem and the onus is on us to deliver, advertise/promote what we have delivered and be honest in what we can deliver.

2 Even if the Holy Grail of automatic target identification is achieved, I do not believe it would solve our RoE problems, I think it would merely create a new set of problems associated with the automation of life or death decisions [45]. This means that not only is “assisted” decision support the most realistic research goal but it is the most desirable one (in the context of guided weapons/targeting/aiming).

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“The Who, What, Where and When of Radar Targeting”

Key Note Speech: Dr Clive Alabaster
(Cranfield University, Shrivenham, UK.)

SET-069 Robust Acquisition of Relocatable Targets using Millimeter Wave Sensors

CONTENT

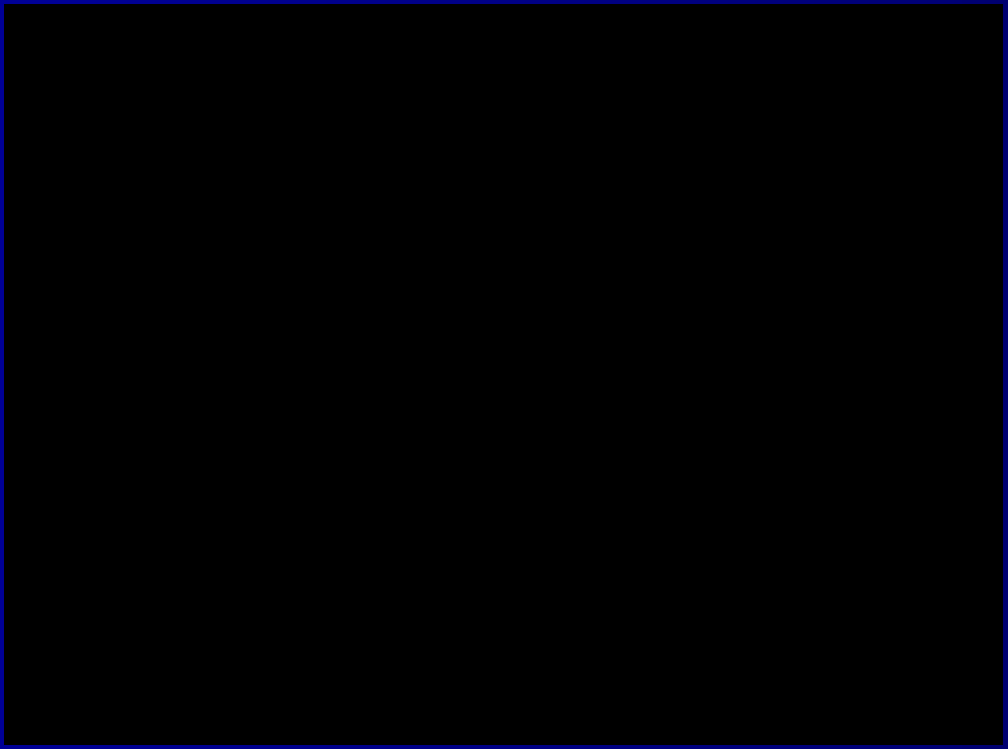
- Existing systems
- Requirement
- Review
  - Problems and solutions
  - Novel and emerging technologies
  - Comparisons with other sensors
- Conclusions
- Questions

EXISTING SYSTEMS

- Airborne Fire Control Radar
- Air launched anti-armour missile seekers
- Terminally guided sub-munitions

EXISTING SYSTEMS – *Airborne FCR*

Longbow FCR



- 35 GHz multi-mode FCR
- Classification of 256 targets
    - Doppler signature analysis
    - Range profiling, polarimetric
- Classification categories:
    - tracked vehicles
    - wheeled vehicles
    - helicopters
    - fixed wing aircraft
    - ADU (with RFI data)
- Prioritises targets
  - 16 highest priority displayed

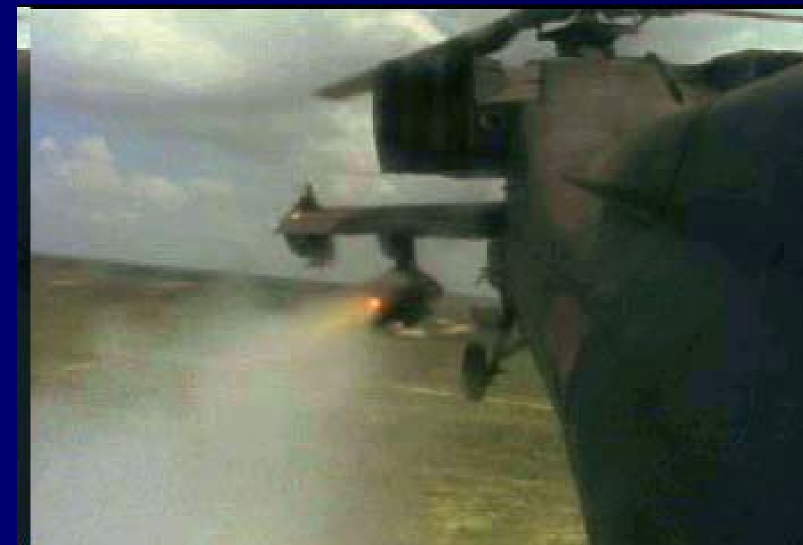
EXISTING SYSTEMS – *Airborne FCR*

Longbow FCR

- Ground and Air targeting and terrain profiling modes
- Pulsed Doppler, Frequency agile
- Pulsed STI mode, Frequency agile, polarisation diverse
- Monopulse angular discrimination (elevation)
- Low Probability of Intercept
- Range vs. tank ~ 8km (moving), 6km (stationary)

EXISTING SYSTEMS – *Air launched anti-armour missile seekers*

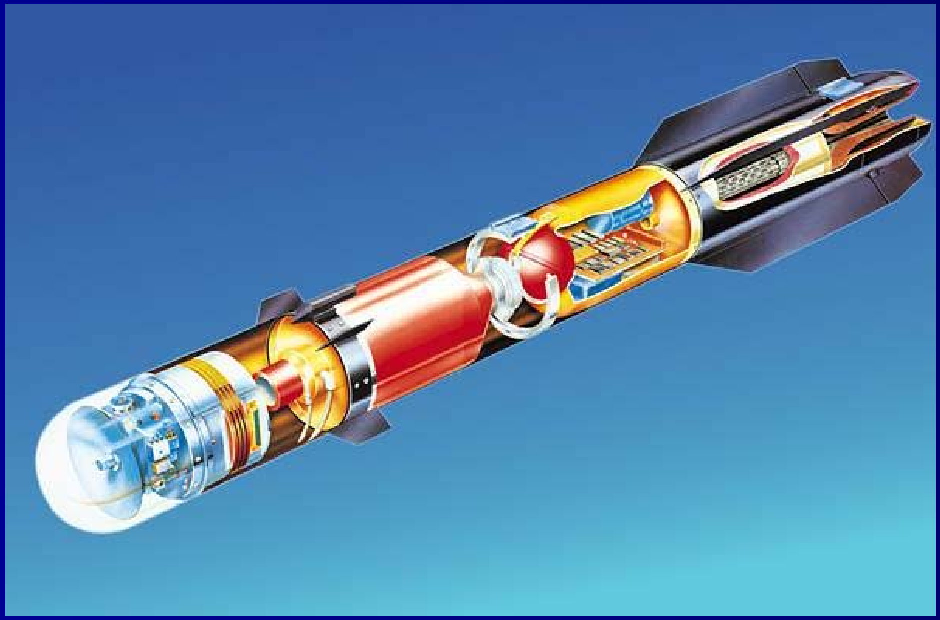
RF Hellfire



- 35GHz active seeker
- Pulsed mode
- Range profiling
- Range vs. tank ~ 3km (estimated)

EXISTING SYSTEMS – *Air launched anti-armour missile seekers*

Brimstone



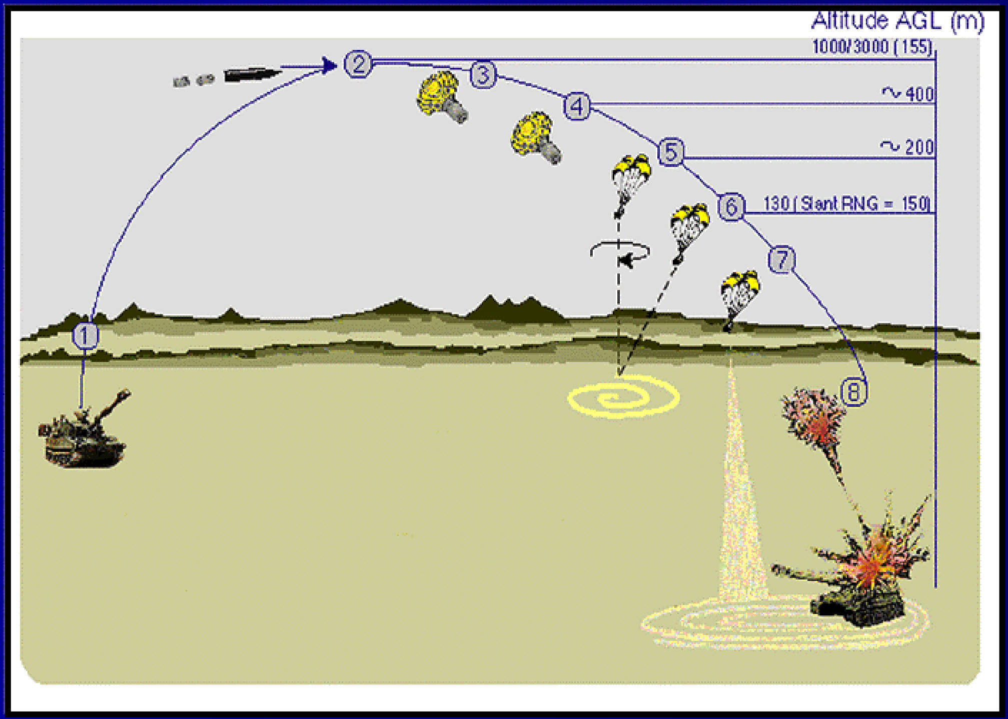
EXISTING SYSTEMS – *Air launched anti-armour missile seekers*

Brimstone

- Air-launched anti-armour missile
- 94GHz imaging radar seeker
- Aim point selection
- Pulsed Doppler, polarisation diverse, pulse compression
- Monopulse angular discrimination
- LPI
- Range vs. tank ~ 2 km (estimated)

EXISTING SYSTEMS – *Terminally guided sub-munition*

SADARM



No ATR facility

- Terminally guided sub-munition
- 94GHz active seeker
- FMCW
- Range vs. tank ~ 100s metres (estimated)

EXISTING SYSTEMS – *Terminally guided sub-munition*

SADARM

FUTURE SYSTEMS

Joint Common Missile (JCM)

Tri-mode seeker

Seeker image

EXISTING SYSTEMS - *Summary*

Applications:

- Target acquisition, prioritisation
- Seekers for terminal phase guidance
- MMW radar likely to be one of several sensors (data fusion)
- Targets are largely land based military vehicles

REQUIREMENT

What drives the requirement for ATR?

- location and identification of targets of interest in wide area imagery to ease the burden on image analysists
- precision attack against legitimate targets
- reduction of fratricide
- assistance to targeting decisions

The "*CNN* effect".

Where is ATR required?

- deep target attack ISTAR
- short range weapons aiming and guidance
- land, air, sea, particularly *ground based* & *littoral waters*

Should we trust a life/death decision to a machine?

REQUIREMENT

The military are not merely interested in recognition and identification but need to know a target's *INTENT.*

The burden of ATR does not necessarily rest solely on radar.

Automatic target identification is the Holy Grail.

What are the targets? This is something we have difficulty in defining.

Automatic target identification can only be met by the data fusion of a multi-sensor, multi-band approach.

Does the "A" in ATR stand for ***Automatic*** or ***Assisted***?
Does the "I" in ATI stand for ***Identification*** or ***Indication***?

REVIEW

- The special nature of (MMW) radar
- Criteria for detection/recognition/identification
- SAR/ISAR imaging
  - Resolution capability
  - Image recognition
- Range profiling
- Novel & emerging ideas
- Comparison with EO imagers

Special Nature of (MMW) Radar

Radar is *active* and *coherent*.

- Leads to direct measurement of *range* and *Doppler*.

Radar uses a long wavelength.

- Leads to *all weather* capability

- Can penetrate dielectrics (foliage, camouflage etc.)

- Low resolution (traditionally)

Special Nature of (MMW) Radar

Use of millimetric wave radar.

- Finer resolution and smaller radars feasible

- Short range

- Radar signature dependent on finer level of detail
  e.g. surface roughness

- Clutter differs

Greater sensitivity to wavelength dependent effects.

- Angular variation

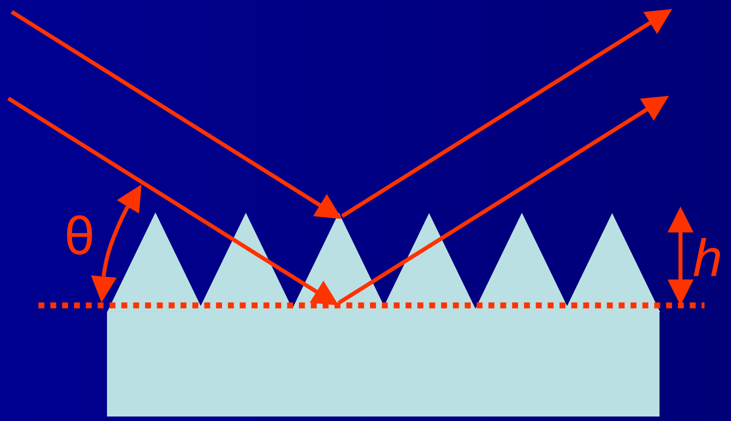
Physics of EM Interaction with Target

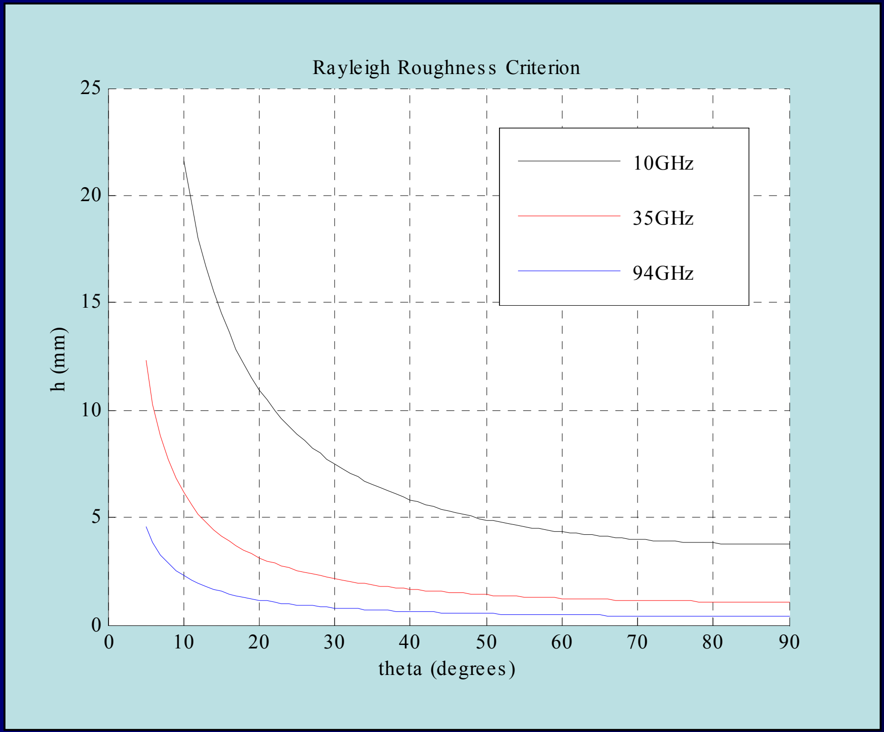
Surface roughness – Rayleigh criterion

Max. phase difference = $\pi/2$

Path length difference = $2h.\sin\theta = \lambda/4$ (max)

h constrained by: $h.\sin\theta < \lambda/8$





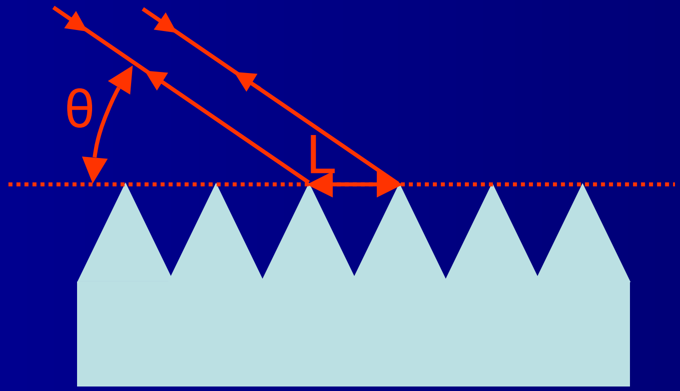
Physics of EM Interaction with Target

Surface roughness – Bragg Scattering

Strong reflection when $L = \dfrac{n.\lambda}{2.\cos\theta}$
(n = 1, 2, 3…)

…and when illuminated
perpendicular to facets

…and when angle at bottom
of groove = 90^0 (for $\theta \geq 45^0$)



There are many strong scattering mechanisms
having strong polarisation characteristics

Physics of EM Interaction with Target

Dielectrics in the MMW band:

- tend to have greater loss tangents
  e.g. water tanδ ~ 0.15 @ 3GHz, 1.2 @ 35GHz, 2 @94GHz
- interference effects from thin layers
  e.g. glass windscreens
- wavelength on same scale as long chain polymer molecules
  e.g. composites
- roughness appears not to be such a dominant factor as one might think
- (diffuse) scattering is highly angular dependent
- roughness may be modelled by inclusion of random phase shifts and/or empirically determined parameters
- roughness better modelled using “exact solver” codes
- target “speckle” is wavelength dependent.

Detection/Recognition/Identification Criteria

Imagery interpretation:

Detection: *the discovery of the existence of an object without its recognition*

Recognition: *The ability to fix the identity of a feature or object within a group type i.e. inter-class discrimination*

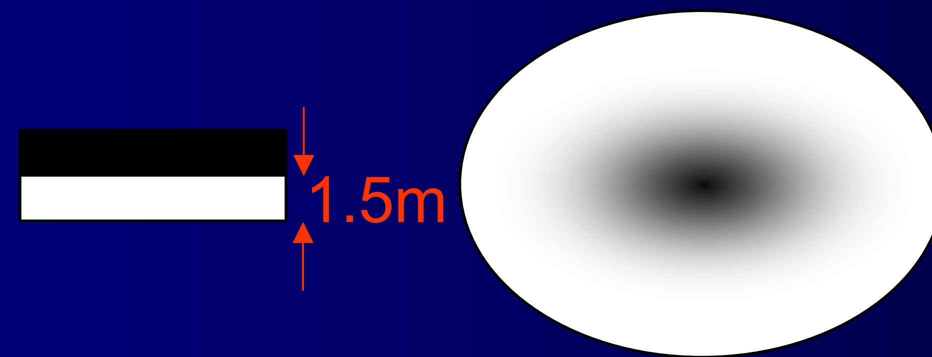
Identification: *The ability to place the identity of a feature as a precise type i.e. intra-class discrimination*

Detection/Recognition/Identification Criteria

The Johnson Criteria

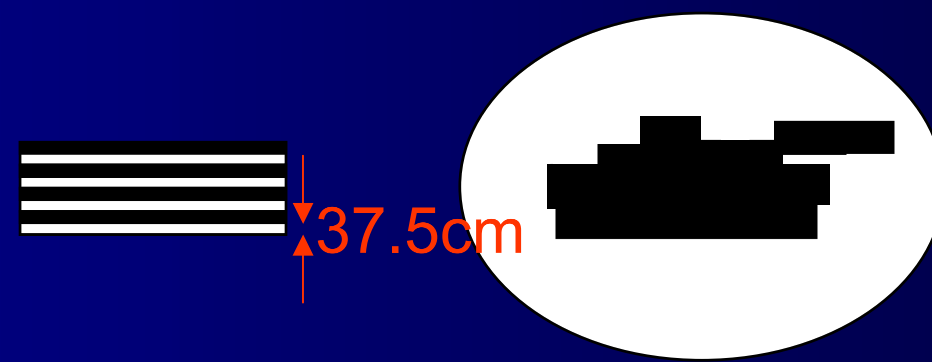
- Detection

1 cycle 2 pixels



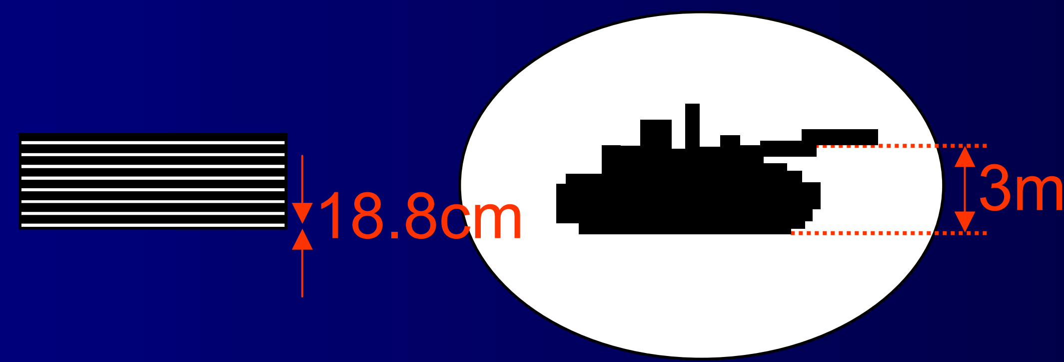
- Recognition

4 cycles 8 pixels



- Identification

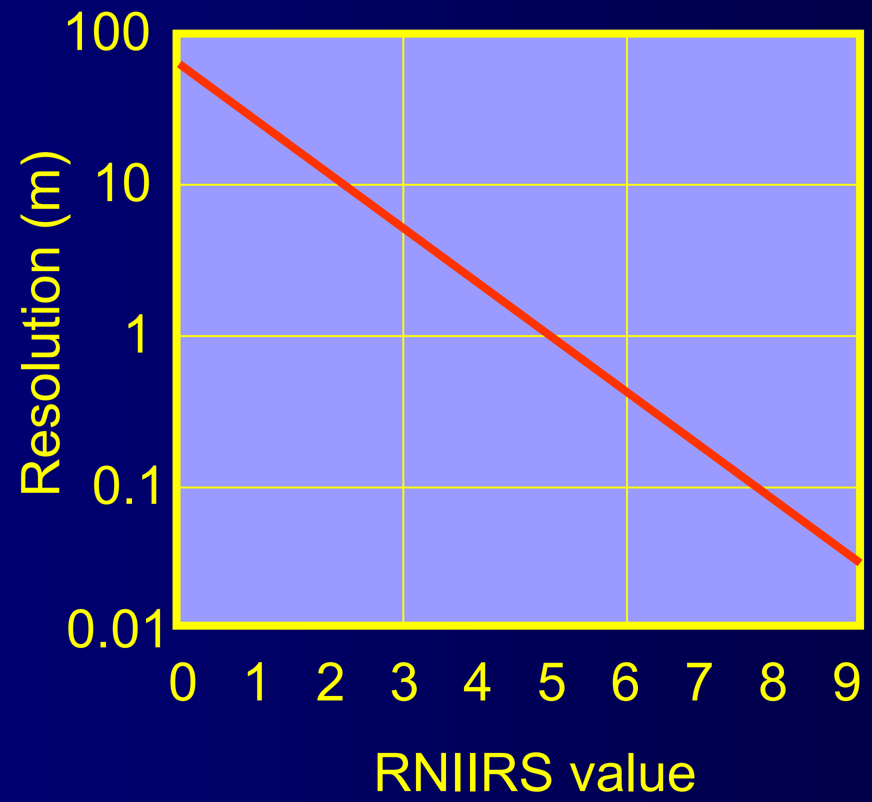
8 cycles 16 pixels



Detection/Recognition/Identification Criteria

The Radar NATO Image Interpretability Rating (RNIIRS)

Capability	RNIIRS
Recognise large static targets	1-2
Detect mobile targets	3-4
Recognise mobile targets	5-6
Identify mobile targets	6-7
Battle damage assessment	7-8



Watchkeeper URD 4002 Annex E

Resolution requirements:
d/r/i = 1.0 to 1.5/0.5/0.15 m

Radar ATR

Can radar provide automatic target recognition?

P_{cc} of 80-95% regularly achieved in "special operating conditions"

BUT

P_{cc} not much better than random chance in realistic battlefield "extended operating conditions"

Extended Operating Conditions:

- obscuration
- environment
- occlusion
- overlapping/nearby targets
- configuration changes
- serial number

Some recent headway

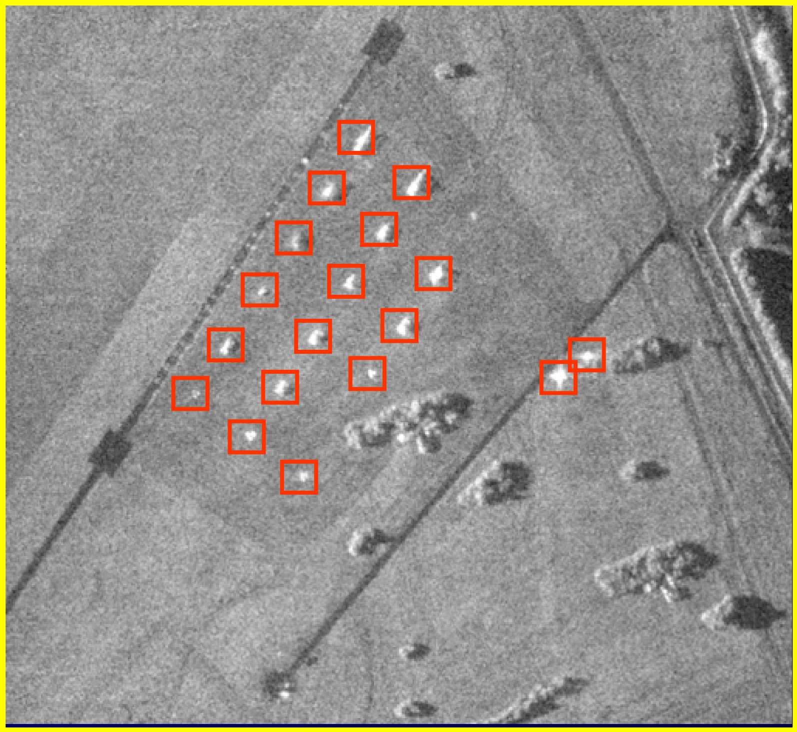
Drive towards an infinite computer

Require the ability to generalise

SAR/ISAR Imaging

State-of-the-art SAR/ISAR can obtain range and cross range resolution down to 10cm.

Target recognition is a matter of data dimensional reduction
e.g. spot-light SAR image of 1km x 1km at 30cm resolution has 10^7 pixels.



This must be reduced to the identification of x targets and the recognition of y target classes dimension xy.

Multiple stages of processing include:
- extraction of “focus of attention” or ROIs e.g. chip sets of 50 x 50 pixels
- image recognition/identification.

Extracting the Regions of Interest

Ideal solution is compromise between performance (P_D & FAR) and speed.

Traditional approach is to scan image with a CFAR window function to detect brightness/contrast changes as ROI. Gaussian clutter assumed.

Problems: False alarms from bright clutter regions,
Contending with realistic clutter.

Realistic clutter (Weibull, K-) leads to non-linear CFAR - computationally more demanding.

Exploitation of spatial properties of targets – also computationally more demanding.

Texture based features – **contextual information**.

Extended Fractal/2 parameter CFAR introduces a size sensitivity (plus brightness/contrast features) – **low FAR, fast**.

Additional Processing Stages

Indexer to label candidate targets. FOAs subjected to a screening process based on size, shape, fill ratio, pattern recognition etc. to reduce false alarms.

Orientation of targets may be determined by applying transforms to detect edge of major axis (Sobel operators, Hough transform, Radon Transform). Orientation to within ~ 10^0, may have 180^0 ambiguity.

Image may be normalised (normalised mean)
i.e. a brightness normalisation.

Target Recognition - *Techniques*

Template matching e.g. use of mean squared error (MSE) algorithm.
Images compared with “training” data.
ROIs declared as target type or dismissed as clutter.

Problems with occluded targets and articulated targets.

Methods based on relative dimensions of scatterers.
Still requires training data.
Optimal number of scatterers (30 – 50).
P_{cc} remains high for 60% occlusion.
Best for targets with large relative distances between scatterers (rather than close clusters).

Statistics of radiometric, geometric and polarimetric features.
No single feature is a robust discriminant.
P_{cc} generally improves with
- resolution (10cm better than 30cm),
- number of features
- known target orientation

Target Recognition - *Techniques*

Neural Networks and evolutionary algorithms.

Statistical methods to determine the class and orientation of the target in an image chip.
Pixel values in chip sets are matched to various PDF.
Pixel values are transformed in an attempt to yield a Gaussian PDF.
Transformation giving best Gaussian fit reveals original PDF of data.
Data PDFs considered are:

- **(Conditionally) Gaussian model.**
  complex pixel vectors Gaussian of zero mean, match to variance.
- Log magnitude model.
  pixel magnitude squared is log normal, match to mean (dB)
- Quarter Power model.
  square root of pixel magnitude is gamma PDF, match to mean.

Requires a windowing and interpolation to refine orientation estimation.

Target Recognition - *Considerations*

Many model based algorithms for ATR are based on a system of *votes* of multiple hypotheses. Various statistical combinations threshold the votes to declare target type.
(Proportional representation *NOT* first past the post.)
Bayesian approach based on mixed models helps achieve generalisation/robustness and greater confidence.

There is an optimum to the model complexity (for fixed size target set).
Reduce data to retain those components which correlate well against model increases performance and reduces computation.

Some algorithms search for positive proof of target type.
OK for limited target set.

Comparison of ATR performance is fraught with difficulty due to the uniqueness of the conditions.

Contextual information invaluable.

Range Profiling

1-D Range profile is a 2D (I)SAR image projected onto the range coordinate, as such it is less computationally demanding. Images processed using (weighted) FFT or HDVI techniques and template matching.

There are difficulties in measuring range extent of targets due to self masking, especially at low grazing angles (depends on how range extent of target is defined).

Range profile is very sensitive to target aspect, particularly at MMW.

Sensitivity to target aspect may be reduced by non-coherent averaging over a span of aspect angles.

P_{cc} improved using multiple looks at multiple aspects spaced at fraction of degree. Long processing intervals reduce target speckle.

P_{cc} sensitive to SCR. Range profiling best adopted for ***moving*** targets.

1-D cross range profiling has been attempted using ISAR techniques (but with little success).

Range Profiling – *Sensitivity to aspect*

HRRP decomposes into scatterer auto term plus scatterer cross term.

SAT depends on:

- Positions and strengths of scatterers – usually fairly consistent over 10^0
- Scatterer shadowing – worse at low grazing angles
- Scatterer migration through range cells (MTRC)

Tolerance condition $\delta\varphi_{MTRC} \leq c/2BL_x$

e.g. B = 500MHz ($\rightarrow R_{res}$ = 0.3m), L_x = 7m gives $\delta\varphi_{MTRC} \leq 2.4^0$

SCT depends on correlation of range profiles at different aspects and is about an order of magnitude more aspect sensitive than SAT at cmW.

e.g. correlation between 2 range profiles reduced to 0.75 over
0.3^0 (1GHz) 0.1^0 (2GHz)

Range Profiling – *Sensitivity to aspect*

Range profiles averaged over span of aspect angles to reduce aspect variation.

ISAR images have much reduced SCT because scatterers are resolved in cross-range dimension. However, a well focussed ISAR image is achieved over an aspect variation of: $\Delta\varphi \geq \lambda/2.\Delta R_x$

e.g. $\Delta R_x = 0.3\text{m}$, $\lambda = 8.6\text{mm}, 3.2\text{mm}$ gives $\Delta\varphi \geq 0.82^0, 0.3^0$

Range profiles must be aligned before averaging – complexity.

Bispectrum methods ease the complexity.
Bispectrum based on Fourier transforms into 2D frequency space.
Bispectrum is invariant to misalignments.
ATR can operate on the bispectrum but is computationally expensive.
Bispectrum slices (axial, radial, diagonal) reduce dimensionality.
Circularly integrated bispectrum found to give best ATR performance.

ISAR image carries more data but averaged range profiling less sensitive to aspect than ISAR image and so is a better choice for ATR.

Radar Vibrometry – *Micro-Doppler*

Interferometry methods similar to laser vibrometry.

Can detect vibrational signature of target (rather than bulk velocity).

Vibration causes phase modulation.

Micron level detection.
Sensitivity improves with increasing frequency.
Requires very low phase noise transmitted signal/LO.

Could determine whether vehicle engine is running.

Potential to detect structural resonances.

Vibration likely to modulate the polarisation of target signature.

Novel SAR Techniques

3-D ISAR imaging on manoeuvring target using 3 receivers in a plane orthogonal to the line of sight.

- 3 offset imaging planes (data is phase shifted).
- yields known cross range (Doppler) scale even if target rotational movement is unknown.
- similar to Lippman photography

Non-linear SAR in which platform flies a curved path to decouple the Doppler history associated with target motion with that due to platform motion.

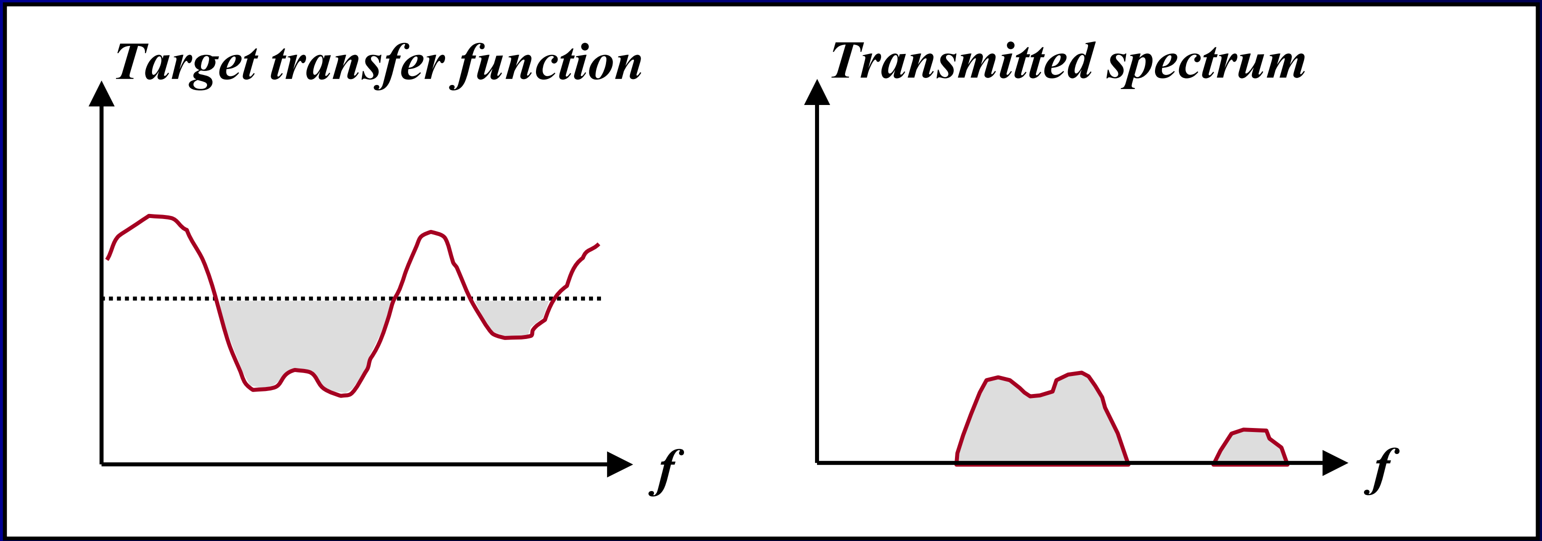
Stepped frequency SAR.

Matched Illumination

For HRRR, maximum SNR is obtained for:

- matched receiver
- matched transmitted waveform
- measure of both.

BUT, maximum target information transfer is obtained for the *inverse* of the above.



Comparison with EO Imaging

EO imagers can achieve cm level resolution in real time.

ATR based on image recognition algorithms; EO sensors do not enjoy such diverse techniques as with radar.

Current image recognition methods for research include:
Fourier descriptors,
Moment invariants,
Hyperspectral imaging,
Various others including synthetic aperture techniques used for astronomy and civilian applications.

ATR in special operating conditions is reliable.

ATR in realistic battlefield situation is poor
(scattering, attenuation through atmosphere is a major problem).

Superior algorithms and computing power required.

Whilst the technology differs Radar and EO sensors are in almost identical situations.

Conclusions

- Radar resolution matches the requirements for EO imagers for recognition/identification.
  Lack of resolution is not the issue.
- Reliable recognition is achievable in benign conditions; but not in a realistic battlefield situation.
- Future advances sought in computing capacity and/or processing algorithms possibly in those techniques which mimic the natural world e.g. neural networks and evolutionary algorithms.
- Better performance likely by fusion of several ATR techniques.
- Several potential methods are under-exploited.
- Even better performance likely by the fusion of multi-sensors in different bands. US Navy ARTIST program.
- Assisted target recognition is the most realistic goal (for a single radar sensor).

Any Questions?